Detection of Molecular Hydrogen Emission Associated with LkHα 264 *

Yoichi Itoh †
Graduate School of Science and Technology, Kobe University,
1-1 Rokkodai, Nada, Kobe, Hyogo 657-8501
yitoh@kobe-u.ac.jp
Koji Sugitani
Institute of Natural Sciences, Nagoya City University,
Mizuho-ku, Nagoya 467-8501
Katsuo Ogura
Kokugakuin University, 4-10-28 Higashi, Shibuya-ku, Tokyo 150-8440
and
Motohide Tamura
National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588

(Received 1999 December 31; accepted 2000 January 1)

Abstract

We have detected emission of molecular hydrogen from a classical T Tauri star, LkHα 264 in the $v = 1-0$ $S(1)$ line at 2.122 μm. The line velocity is coincident with the rest velocity of the star. The line profile is well reproduced by a model in which the line emanates from material in a Keplerian rotating circumstellar disk. Fluorescence by X-ray ionization and shock excitation due to accretion or a low-velocity wind are considered for the emission mechanism of molecular hydrogen.

Key words: stars: pre-main sequence — stars: individual (LkHα 264) — circumstellar matter

1. Introduction

A star is accompanied by circumstellar materials during its formation phase. Such materials are often recognized by their characteristic spectral features. A circumstellar disk is detected by continuum excess in the infrared and millimeter wavelengths. Accretion from a circumstellar disk onto the stellar surface often produces continuum emission in the X-ray,

* Based on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan

† A guest investigator of the UK Astronomy Data Centre

the ultraviolet wavelengths, and the optical wavelengths. It also generates permitted emission lines, such as the Hα line. An outflow phenomenon is commonly traced by optical forbidden lines and by emission lines of CO and other species in the radio wavelengths. However, even though molecular hydrogen is considered to be the most abundant element in a young stellar disk system, it has so far been detected toward only few T Tauri stars (TTSs). This is because H_2 does not have dipole moment.

Molecular hydrogen is excited in two ways. One way is excitation by shock. Herbst et al. (1996) detected molecular hydrogen emission associated with T Tau. Based primarily on the $2-1/1-0$ $S(1)$ ratio, they conclude that shock heating is a major excitation mechanism for the emission. The shock occurs where an outflow from the central binary interacts with an ambient molecular cloud. Otherwise, the shock may occur in an impact of accretion gas onto a photosphere.

Another way of exciting molecular hydrogen is fluorescence by ultraviolet or X-ray emission. Thi et al. (1999) reported detection of H_2 emission lines toward GG Tau in the mid-infrared wavelengths. They claim that ultraviolet emission at the star-disk boundary excites molecular hydrogen. Weintraub et al. (2000) detected the H_2 $v = 1-0$ $S(1)$ line toward a classical TTS (CTTS), TW Hya. Because the flux of the line is in agreement with that predicted by an X-ray excitation model (Maloney et al. 1996), and because the line peak is coincident with the rest velocity of the central star, they attribute this emission to X-ray excitation. Recently, Bary et al. (2002) and Bary et al. (2003) also detected a fluorescent H_2 $v = 1-0S(1)$ line from three other TTSs (DoAr 21, GG Tau, and LkCa 15).

We present here high-resolution near-infrared spectroscopy of LkHα 264. This star is a CTTS with a spectral type of K5. Its apparent magnitude is $V \sim 12$ (Herbig & Bell 1988) with a visual extinction of $A_V \sim 0.5$ mag. The spectral energy distribution of LkHα 264 has a signature of a circumstellar disk in the mid-infrared wavelengths (Jayawardhana et al. 2001) and in the millimeter wavelengths (Itoh et al. 2003). The mass of the circumstellar disk is estimated to be 0.085 $M_\odot$ (Itoh et al. 2003). This star also exhibits a continuum excess in the blue region of the optical wavelengths (Valenti et al. 1993) and strong emission lines in the ultraviolet wavelengths (Gameiro et al. 1993; Costa et al. 1999). With these characteristics as well as time variations of the continuum and emission lines (Lago & Gameiro 1998; Gameiro et al. 2002), LkHα 264 displays most of the known properties of CTTSs.

LkHα 264 is associated with a high-latitude cloud, MBM 12 (Magnani et al. 1985). Sixteen TTSs are known so far to be associated with this cloud (Ogura et al. 2003). The distance to the cloud has been thought to be around 65 pc (Hobbs et al. 1986; Hearty et al. 2000a). However, recent studies of the stars projected in the field of MBM 12 have indicated significantly larger distances around 300 pc (Luhman 2001; Andersson et al. 2002; Straizys et al. 2002).

This is one of our series of papers on the TTSs in MBM 12; we have carried out detailed

studies of those stars, in order to detect associated faint companions and disk structures, and to investigate their nature. In this Letter, we focus on an emission line of molecular hydrogen associated with LkHα 264. The other features detected by the observations will be discussed in subsequent papers.

2. Observations and Data Reduction

High-resolution spectroscopic observations were carried out on 2002 September 16 with the Infrared Camera and Spectrograph (IRCS) on the Subaru Telescope at the summit of Mauna Kea, Hawaii. IRCS has a 1024×1024 InSb array with a spatial scale of $0\farcs060$ pixel^{-1} for echelle spectroscopy. The echelle with the K^* configuration provides a wavelength coverage of 1.90 μm – 2.45 μm. The width of the slit we used is $0\farcs155$. The resolving power is measured to be 20900 at 2.12 μm, using single and strong OH lines. It corresponds to a velocity resolution of ~ 14 km s^{-1}. The typical seeing size was $0\farcs4$ at 2 μm within a stable condition. Four exposures were taken with the telescope dithered approximately $3\farcs2$ along the slit for sky subtraction. The total integration time is 600 seconds. SAO 75672 (A0, $V = 9.1$) was observed for correcting the effects of telluric absorption. Exposures to a halogen lamp on and off were taken at the end of the night.

The Image Reduction and Analysis Facility (IRAF) software was used for all data reduction. First, a dithered pair of object frames were subtracted from each other, then divided by a flat field. Next, we extracted an image of each order of the echelle spectra using the APALL task with a "strip" option. Then, each image was geometrically transformed to correct the curvature of the slit image. The solution of the wavelength calibration was derived from OH lines using the IDENTIFY task and the FITCOORDS task. The wavelength can be varied as large as 0.3 Å (4 km s^{-1}) by different orders of the fitting function in the FITCOORDS task. Individual spectra were extracted from the transformed images using the APALL task. The region where the flux density of the object is more than 20% of the peak flux density at each wavelength was summed into a one-dimensional spectrum. The object spectrum was divided by the standard star spectrum, and multiplied by a blackbody spectrum of a temperature appropriate to the spectral type of the standard star (Tokunaga 2000). The extracted spectra were then normalized and combined to produce a final spectrum.

3. Result

A high-resolution spectrum of LkHα 264 around 2.122 μm is shown in Figure 1. We detected the H_2 $v = 1 - 0$ $S(1)$ line in emission and other metallic lines (Al, Fe, Mg, and Si) in absorption.

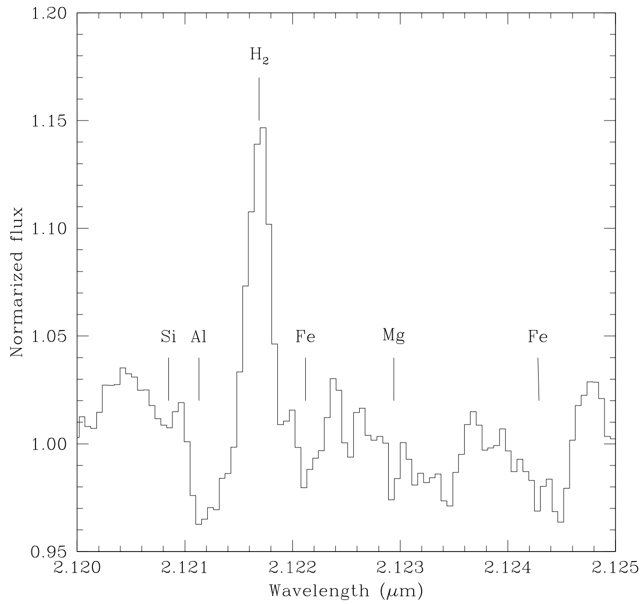

Fig. 1. Echelle spectrum of LkHα 264 around the H_2 $v = 1 - 0$ $S(1)$ line. The spectrum is not corrected for v_{LSR} of the star.

3.1. Rest Velocity of the Star

We measured v_{LSR} of LkHα 264 with the Si line (λ = 2.1210 μm) and the Fe line (λ=2.1244 μm). These lines are deep and sharp absorption lines near the molecular hydrogen line (Weintraub et al. 2000). v_{LSR} is measured to be -5.9 km s^{-1} with $\sigma = 2.8$ km s^{-1}. Change of v_{LSR} due to the Earth's rotation during the observation was as small as 0.01 km s^{-1}. Heliocentric velocity of LkHα 264 have been measured to be $+9.0$ km s^{-1} (Herbig 1977), which corresponds to $v_{LSR} = +1.0 \pm 3.9$ km s^{-1}, whereas Hearty et al. (2000b) derived $v_{LSR} = -4.2 \pm 2.5$ km s^{-1}. v_{LSR} derived from our observations is in agreement with that of Hearty et al. (2000b).

3.2. Molecular Hydrogen Emission Line

The central wavelength of the molecular hydrogen emission line is measured to be $2.121685 \pm 0.000008\mu$m by a gaussian fitting. It corresponds to $v_{LSR} = -5.1 \pm 1.2$ km s^{-1}. Therefore, we conclude that the velocity of the molecular hydrogen line is coincident with the rest velocity of the central star. The emission line is symmetric and is not spatially resolved. The FWHM of the line is measured to be 2.1 ± 0.3Å, which corresponds to a width of 30 ± 4 km s^{-1}. The equivalent width of the line is derived to be -0.33 ± 0.06Å. Compared with the K-band magnitude of the star, we estimate the flux of the line to be $(3.7 \pm 0.6) \times 10^{-14}$ erg s^{-1} cm^{-2}, or a luminosity of $(1.0 \pm 0.2) \times 10^{-4}$ L$\odot$ for $d = 300$ pc. In the measurement above, we have estimated two kinds of uncertainties. One is the uncertainties of the adjacent continuum level of the line. The second is the deviations among the individual spectra. We measured the

line profile in the spectra before combining. Finally, we considered larger values in these two values as the uncertainties of the measurement.

We did not detect the H_2 $v = 1-0$ $S(0)$ line and the H_2 $v = 2-1$ $S(1)$ line, with 3σ upper limits of 9.4×10^{-15} erg s^{-1} cm^{-2} for both lines. Therefore, the line ratios of $v = 2-1$ $S(1)$ and of $v = 1-0$ $S(0)$ to $v = 1-0$ $S(1)$ are less than 0.26 for LkHα 264.

The mass of molecular hydrogen can be estimated from the flux of the line. Assuming an LTE condition with an exciting temperature of 1500 K and using equations (1) and (2) of Bary et al. (2003), we derive the mass of hot molecular hydrogen to be 7×10^{-7} M$_\odot$. However, this mass is thought to be only a small fraction of the total disk mass. Adopting a scale factor relating hot H_2 to the total disk mass ($10^7 \sim 10^9$; Bary et al. 2003), we derive a total disk mass of $7 \sim 700$ M$_\odot$. Such a heavy disk around a TTS is not realistic, because it should break immediately by strong fragmentation. The small scale factor which indicates efficient emission of molecular hydrogen should be applied for LkHα 264.

An alternative explanation is that the distance to the object is 65 pc. Using this distance with the same formulae above, we derive the mass of the hot molecular hydrogen to be 3×10^{-8} M$_\odot$ and the total disk mass to be $0.3 \sim 30$ M$_\odot$. Such estimates would be reasonable for a disk around LkHα 264, especially at the lower value.

3.3. Optical Spectra

No optical forbidden emission lines have so far been detected from LkHα 264 (e.g. Gameiro et al. 2002). We investigated the optical spectra of the star in the ING Archive. The data were obtained on 2000 Oct. 12 using the Issac Newton Telescope. The integration time is 600 sec. The wavelength coverage is between 3000 Å and 9000 Å with a spectral resolution of ~ 4000. We find no forbidden emission lines with an upper limit of 4.2×10^{-15} erg s^{-1} cm^{-2} (1.2×10^{-5} L$_\odot$) for the [O I] line at 6300 Å. Hartigan et al. (1995) surveyed optical forbidden lines toward TTSs in the Taurus molecular cloud. They detected the [O I] line for all CTTSs, while they did not detect the line for all weak-line TTSs with an upper limit of $\sim 4 \times 10^{-6}$ L$_\odot$. LkHα 264 does not show any forbidden lines as strong as those in the CTTSs. Therefore, this star does not have such an active outflow as most CTTSs do.

4. Discussion

4.1. Excitation Mechanism of the Molecular Hydrogen Emission Line

Molecular Hydrogen can emit the $v = 1-0$ $S(1)$ line through fluorescence by X-ray or UV photons. The emission can also be due to shock caused by accretion, by a low velocity wind, or by a high velocity jet. In the following we will examine these possibilities.

4.1.1. *Fluorescent Emission*

Fluorescent emissions of molecular hydrogen excited by X-ray or UV photons are found for several TTSs (Thi et al. 1999; Weintraub et al. 2000; Bary et al. 2002; Bary et al. 2003). Weintraub et al. (2000) detected the H_2 $v = 1-0$ $S(1)$ emission line toward TW Hya. Since the velocity of the line is coincident with that of the central star, they attribute the emission to fluorescence. The same interpretation is made for DoAr 21 (Bary et al. 2002), GG Tau, and LkCa 15 (Bary et al. 2003). The line velocity for LkHα 264 is also consistent with the velocity of the star. Therefore, the line seems to be of fluorescent emission. However, the flux ratio of the $v = 2-1$ $S(1)$ line to the $v = 1-0$ $S(1)$ line is ~ 0.5 for emission induced purely by ultraviolet fluorescence (Black & van Dishoeck 1987). This ratio is measured to be less than 0.26 for LkHα 264, indicating that the emission is not induced by pure ultraviolet fluorescence.

X-ray excitation of molecular hydrogen has been investigated for several kinds of objects. Tine et al. (1997) consider an interstellar cloud heated by X-rays. For some cases in the model, for instance $T = 2000$ K and $n = 10^5$ cm^{-3}, the predicted line ratios of $v = 2-1$ $S(1)$ and $v = 1-0$ $S(0)$ to $v = 1-0$ $S(1)$ are consistent with the observed ratios.

If the H_2 emission line emanates from a circumstellar disk by X-ray excitation, we predict the $1-0$ $S(1)$ line intensity following Bary et al. (2003). The X-ray luminosity of LkHα 264 has been measured to be $10^{28.4}$ erg s^{-1}, assuming a distance to the star of 65 pc (Hearty et al. 2000a). It corresponds to $10^{29.7}$ erg s^{-1} for $d = 300$ pc. Using the equations in Maloney et al. (1996), we estimate the X-ray energy deposition rate per particle, H_X, to be 8.5×10^{-24} erg s^{-1} at a distance of 10 AU from the source. With Figure 6a of Maloney et al. (1996), we find that the line intensity would be $\sim 10^{-4.5}$ erg s^{-1} cm^{-22} str^{-1} for a plausible H_2 disk density of $n = 10^5$ cm^{-3} and a hydrogen column density between the source and the emitting gas of 10^{22} cm^{-2}. The excitation temperature of H_2 is between 1000 K and 2000 K (Bary et al. 2003). Assuming an annulus between 10 AU and 30 AU in a circumstellar disk for the emitting region, the line flux would be $\sim 2.1 \times 10^{-17}$ erg s^{-1} cm^{-2}. For $d = 65$ pc, we find $H_X = 4.3 \times 10^{-25}$ erg s^{-1}, and the line flux $\sim 4.5 \times 10^{-17}$ erg s^{-1} cm^{-2}. In either cases, the predicted line flux is three orders of magnitude smaller than the observed values.

4.1.2. *Shock Excitation*

Another mechanism inducing molecular hydrogen emission is shock excitation. Molecular hydrogen emission lines are often observed toward shock phenomena, such as Herbig-Haro objects. H_2 emission lines from a T Tau binary system are well interpreted by shock excitation of outflow or accretion (Herbst et al. 1996). However, LkHα 264 does not have any signature of shock, such as optical forbidden lines or associated Herbig-Haro objects or CO outflows.

First, we consider a shock by an unidentified jet. In this case, the jet should not extend over 60 AU, because the H_2 emission is not spatially resolved. Moreover, the jet should be highly

inclined with respect to the line of sight, because the emission line is not largely blueshifted. With such a jet, a circumstellar disk around the star would shade the light of the central star. Therefore, it is unlikely that a shock by an unidentified jet makes the emission line.

Accretion of matter in a circumstellar disk onto the central star may account for the line emission (Herbst et al. 1996). Such accretion generally redshifts a line. Because the molecular hydrogen line of LkHα 264 does not have a high velocity relative to the star, pole-on geometry is required for this mechanism.

Hartigan et al. (1995) consider shock excitation by wind associated with a circumstellar disk for low-velocity components of optical forbidden lines toward CTTSs. They revealed that such components often have small negative radial velocities (~ 5 km s^{-1}). Since the velocities of the star and the emission line for LkHα 264 have relatively large uncertainties, we cannot reject the possibility that the line is slightly blueshifted.

In summary, possible shock mechanisms inducing the molecular hydrogen emission are due to disk wind or accretion. Further precise velocity measurements are required in order to determine the excitation mechanism.

4.2. The Line Profile of the Molecular Hydrogen Emission Line

The line width of the molecular hydrogen line is significantly larger than the resolution of the observations. Even though we cannot determine whether molecular hydrogen is being excited in fluorescent or by shock, we can infer that the emission is associated with a circumstellar disk except for shock by accretion. A line profile is broadened, if the emitting material rotates in a circumstellar disk. We construct a simple model for the line profile, following the model of Hartigan et al. (1995). We assume a Keplerian rotating disk. A line profile generated by a ring of material in the disk has a double-peak, with the two maxima occurring at $V_{max} = \pm V \sin i$, where V is the orbital velocity of the ring and i is inclination. We assume the surface brightness of the emitting material in a power law according to the radius ($\propto r^{\nu}$). The outer radius of the disk (r_{out}) does not affect the line profile significantly. We set an outer radius of 30 AU. The line is smoothed by a gaussian function of the instrument profile measured by OH lines.

The predicted H_2 emission lines with the observed line are shown in Figure 2. General behaviors of the line profiles are as follows; Pole-on geometry makes a narrower profile than edge-on; A steep power law in brightness generates a wider profile; Emission from the region between 0.1 AU and 1 AU makes the line profile wider or adds a wing to the profile. The disk models that are consistent with the observed line profiles are models with $\nu = -2.5$, r_{in}(the inner radius of the disk)$= 0.1$ AU, $i = 15°$, with $\nu = -2.5$, $r_{in} = 1$ AU, $i = 75°$, with $\nu = -3.0$, $r_{in} = 0.1$ AU, $i = 15°$, and with $\nu = -3.0$, $r_{in} = 1$ AU, $i = 45°$. Hartigan et al. (1995) found $\nu \sim -2.2$ for optical [O I] lines for two CTTSs. For LkHα 264, the models with $\nu = -2.2$ make narrower lines than the observed line with any inner radius or any inclination.

An emission line from a circumstellar disk often has a double-peak. The line tends to

have a double-peak, if the inclination is large and/or if the inner region of the disk emits a large portion of the emission. For example, the line is resolved in a double-peak for a model with $\nu = -3.0$, $r_{in} = 1$ AU, $r_{out} = 10$ AU, and $i = 75°$. If the emission emanates not only from the inner region but also from the outer region, a large negative number is required in ν for a double-peak. Since we assume a Keplerian rotating disk, $v \propto r^{1/2}$. Therefore, a width of an annulus, Δr, in which the material rotates between v and $v + \Delta v$ is $\propto r^2$. An area of such an annulus is $2\pi r \Delta r \propto r^3$. Therefore, in the case of $\nu > -3$, the outer region of the disk emits a large portion of the emission, and the line tends to have a single-peak. On the other hand, for $\nu < -3$, since the inner region emits a large portion of the emission, the line tends to have a double-peak. For example, the line is resolved in a double-peak for a model with $\nu = -3.5$, $r_{in} = 1$ AU, $r_{out} = 30$ AU, and $i = 75°$. Though we cannot reject the possibility that the line has a double-peak with a small velocity separation, two models above are, at least, inconsistent with the observed line profile.

We considered that the X-ray induced H_2 emission may emanate from an annulus between 10 AU and 30 AU in a disk. However, the model with $r_{in} = 10$ AU and $r_{out} = 30$ AU produces the line somewhat narrower than the observed line profile, with any i and ν. Nevertheless, because the temperature distribution of the disk, therefore r_{in} and r_{out} could vary with the disk shape, we cannot reject the X-ray induced mechanism.

The spectral energy distribution of LkHα 264 indicates the inner radius of the disk to be 0.08 AU (Itoh et al. 2003). We speculate, for the case of $r_{in} = 1$ AU, that the circumstellar disk is thin and flat within 1 AU and is flared beyond 1 AU. For such a disk, X-ray or shock by disk wind much affects the disk surface beyond 1 AU, whereas little within 1 AU. Otherwise, hydrogen exists within 1 AU in the form of an atom or be ionized. The other explanation is that gas is depleted within 1 AU. Alternatively, for disk wind shock, Safier (1993) predicts that forbidden lines and atomic hydrogen emission lines emanate from a circumstellar disk within 1 AU, while molecular hydrogen lines arise from a region beyond 1 AU.

We are grateful to H. Terada and R. Potter for help with the observations. This research is partially based on data from the ING Archive. Y. I. is supported by the Sumitomo Foundation. This study is also supported by Grands-in-Aid from the Ministry of Education, Culture, Sports, Science, and Technology of Japan (14540228 for K. S. and Y. I., and 15540238 for K. O.).

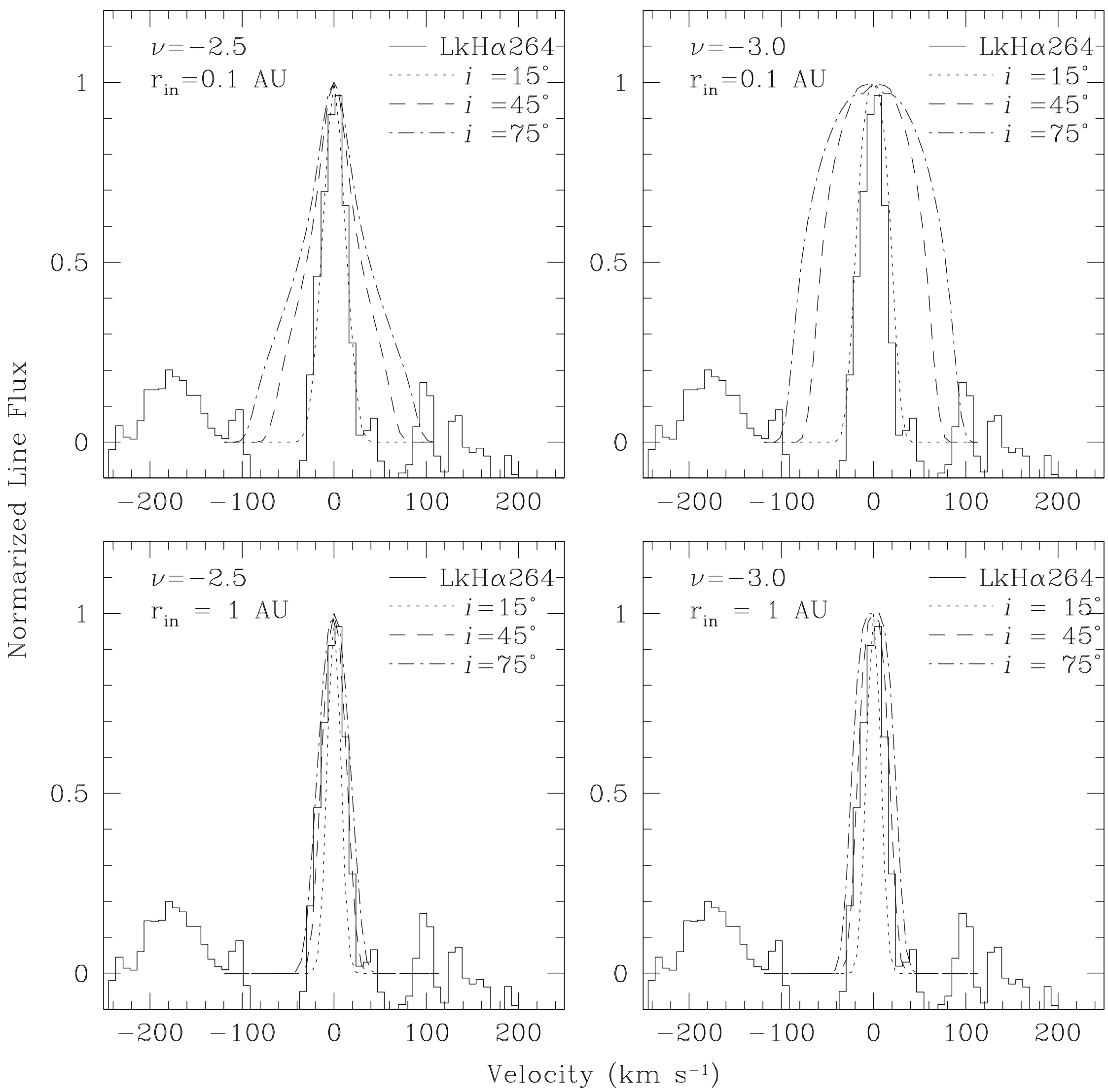

Fig. 2. The observed H_2 $v = 1-0$ $S(1)$ emission line with the emission lines predicted by the models in which the emission emanates from material in a circumstellar disk.

References

Andersson, B.-G., Idzi, R., Uomoto, A., Wannier, P. G., Chen, B., Jorgensen, A. M. 2002, AJ, 124, 2164

Bary, J. S., Weintraub, D. A., & Kastner, J. H. 2002, ApJ, 576, L73

Bary, J. S., Weintraub, D. A., & Kastner, J. H. 2003, ApJ, 586, 1136

Black, J. H. & van Dishoeck, E. F. 1987, ApJ, 322, 412

Costa, V. M., Gameiro, J. F., Lago, M. T. V. T. 1999, MNRAS, 307, L23

Gameiro, J. F., Lago, M. T. V. T., Lima, N. M., Cameron, A. C. 1993, MNRAS, 261, 11

Gameiro, J. F., Fohla, D. F. M., & Costa, V. M. 2002, A&A, 388, 504

Hartigan, P., Edwards, S., & Ghandour, L. 1995, ApJ, 452, 736

Hearty, T., Fernandez, J. M., Alcala, J. M., Covino, E., Neuhauser, R. 2000a, A&A, 357, 681

Hearty, T., Neuhauser, R., Stelzer, B., Fernandez, J. M., Alcala, J. M., Covino, E., Hambaryan, V. 2000b, A&A, 353, 1044

Herbig, G. H. 1977 ApJ, 214, 747

Herbig, G. H., Bell, K. R. 1988, Lick Observatory Bulletin 1111, 1

Herbst, T. M., Beckwith, S. V. W., Glindemann, A., Tacconi-Garman, L. E., Kroker, H., Krabbe, A. 1996, AJ, 111, 2403

Hobbs, L. M., Blitz, L., Magnani, L. 1986, ApJ, 306, L109

Itoh, Y., Sugitani, K., Ogura, K., Fukuda, N., Tamura, M., Marui, K., Fujita, K., Nakanishi, K., Oasa, Y., Fukagawa, M. 2003, ApJ, 586, L141

Jayawardhana, R., Wolk, S. J., Barrado y Navascues, D., Telesco, C. M. Hearty, T. J. 2001, ApJ, 550, L197

Lago, M. T. V. T., Gameiro, J. F. 1998, MNRAS, 294, 272

Luhman, K. L. 2001, ApJ, 560, 287

Magnani, L., Blitz, L., Mundy, L. 1985, ApJ, 295, 402

Maloney, P. R., Hollenbach, D. J., & Tielens, A. G. G. M. 1996, ApJ, 466, 561

Ogura, K., Sugitani, K., Magakian, T. Y., Movsessian, T. A., Nikogossian, E. H., Itoh, Y., Tamura, M. 2003, PASJ, August issue

Safier, P. N. 1993, ApJ, 408, 115

Straizys, V., Cernis, K., Kazlaukas, K., Laugalys, V. 2002, Baltic Astronomy, 11, 231

Thi, W., van Dishoeck, E. F., Blake, G. A., van Zadelhoff, G., Hogerheijde, M. R. 1999, ApJ, 521, L63

Tine, S., Lepp, S., Gredel, R., Dalgarno, A. 1997, ApJ, 481, 282

Tokunaga, A. T. 2000, in Astrophysical Quantities, ed. A. N. Cox (Springer-Verlag), 143

Valenti, J. A., Basri, G., Johns, C. M. 1993, AJ, 106, 2024

Weintraub, D. A., Kastner, J. H., & Bary, J. S. 2000, ApJ, 541, 767